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Heat supply planning for the ecological housing community Munksøgård

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ABSTRACT

Munksøgård is a housing community near the city of Roskilde, Denmark. In 2014, Munksøgård's residents have agreed to change the existing heat supply system. The choice of future heat supply was narrowed to heat pumps, new biomass boiler and connection to nearby district heating network.

The present paper compares results from techno-economic energy system analysis, simple private-economic analysis and assessment of externalities related to the heat supply and discusses the differences in conclusions - is the economic optimal solution different from a system or private-economic point of view?

The techno-economic energy system analysis is done using TIMES-DTU model, which optimizes over all sectors in Denmark and all periods until 2050. The result from this model gives the least expensive solution from the overall system point of view. A spreadsheet model has been developed to do the private-economic analysis and the evaluation of external effects related to the different solutions.

KEYWORDS

National energy system, local energy system, energy system modelling, renewable energy, district heating, heat supply, private-economy, socio-economy

INTRODUCTION

Danish energy system is heading towards a renewable energy based future in 2050. Few other national targets should be met along the way [1, 2]: renewable energy should account for more than 35 % of final energy consumption in 2020, while approximately 50 % of Danish electricity consumption needs to be produced from wind power starting from 2020. Furthermore, the intention of the Danish Government is that electricity and heat generation has to be 100% renewable by 2035, and the power plants should not burn coal from 2030 etc.

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Despite established and clearly defined national targets, lower administrative units such as regions and municipalities are not obliged to have their own targets for transition to renewable energy. For example, Central Denmark Region has set a goal for renewable energy share to 50 % in 2025 [3]. Zealand Region aims for 18 % of wind power and 27 % of regional biomass in region's energy consumption in 2020 [4]. North Denmark Region decided to have a 2 % reduction in CO₂ emissions until 2025 [5]. Different goals can be seen on municipal level as well – Samsø's net balance over a year is 100% renewable for 10 years [6], Rinkøbing-Skjern expects to be 100 % self-sufficient with renewable energy in 2020 [7], while the municipalities Copenhagen and Aarhus are planning to be CO₂ neutral in 2025 and 2030, respectively [8, 9]. Below the municipal level, specific renewable energy targets are not set. On that level, district heating companies are deciding on the type of fuel, while private consumers are the ones making decisions on type of heating supply (district heating, heat pumps, oil boiler, etc.), mean of transportation (bicycle, train, gasoline car, etc.), heat and electricity savings, etc.

Energy system analysis received a lot of attention at the national level. Different aspects of the Danish energy system were the topics of several studies - Danish energy system as a whole was analysed for the years 2030 and 2050 in [10], role of district heating was addressed in [11-13], individual heat pumps in [14, 15], profitable heat savings in [16,17], optimization of waste treatment in [18, 19]. At a municipal level, district heating in Copenhagen was analysed in [20], low-temperature district heating and competition between district heating and heat savings in Frederikshavn in [21, 22], while a renewable energy scenario [23] and integration of renewables [24, 25] were analysed for Aalborg municipality.

When it comes to smaller geographical areas such as groups of buildings or a housing community, energy system analysis is usually not applied. At such geographical scales, results from demonstrations or measurement projects are usually reported or operational aspects of a specific technology are discussed. In accordance with this, Bøhm presented results of measurements of consumption, efficiency and losses in domestic hot water systems in 15 residential and public buildings [26]. Harrestrup and Svendsen [27] done measurements of heat consumption before and after the renovation of a multi-storey building in Copenhagen with heritage value and reported reduction of heat consumption of 47 %, which proved to be within expected values. Morelli et al. [28] used a multi-storey building in Copenhagen from 1896 as a case-study for three types of energy retrofit measures and concluded that the reduction of energy consumption by 68 % is achievable, but renewable energy sources are needed to achieve a “nearly-zero” energy building. Mørck et al. [29] have investigated cost-effective, low-energy buildings within the demonstration project Class 1 in housing community Stenløse Syd. They have done measurements of gross energy consumption and discovered that it is 180% higher than the expected and discussed possible explanations. The choice of heat supply system or whether to renovate a group of buildings largely depends on private-economy and private preferences.

There is a consensus among residents of the ecological housing community Munksøgård that the existing heating system needs to be changed. The present paper presents three views on the question "Which heat supply system should be chosen by Munksøgård?". First, national energy system analysis until 2050 is performed by TIMES-DTU model. The results from this analysis represent optimal solution for the Danish energy system as a whole; Munksøgård is not explicitly modelled. After that, analysis of Munksøgård's local energy system is performed by a spreadsheet model. These results are based on private-economy and externalities such as local pollution, noise or stability of supply. Third view on the new heat supply system will be

determined in the democratic voting process. Finally, the differences between solutions will be presented and the need for making socio-economically suitable solutions attractive to private consumers will be identified.

THE MUNKSØGÅRD COMMUNITY

Munksøgård is an eco-village built in year 2000 (www.munksoegaard.dk). The idea was to create a village-like community with focus on resources, environment and local involvement. To create a mixed community of people, the apartments have different sizes and are a mix of rental, share owned and private owned apartments. One group is reserved for younger people, one for older and three for families, as presented in Figure 1. These five groups consist of 20 apartments each and the total amount of people is around 250.

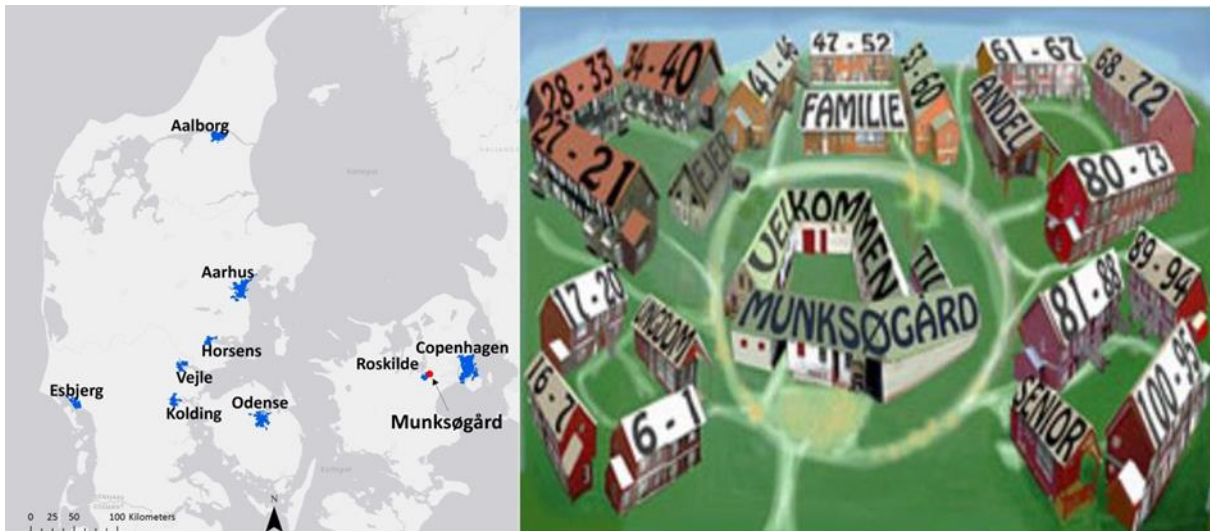


Figure 1. Munksøgård is placed in the periphery of Roskilde city, which is 40 km west of Copenhagen. It consists of 5 groups of building constructed around an old farm house.

The special solutions applied at Munksøgård are local district heating system with wood pellet boilers supplemented with solar heating, local waste water treatment system, separation of urine in the toilets, relatively efficient buildings, use of rain water for washing machines and a big green area for gardens and animals (sheep, cattle, pigs, etc.). The village is placed on the edge of Roskilde city having land-zone area on one side and city-zone on the other side.

The community builds on local involvement. Maintenance of sewage system, heating system, green areas and buildings is carried out by the residents. There is a democratic structure with a steering board with 2 persons from each group elected every year for a one year period. The decision power is placed at the general assembly which is meeting twice a year where all households at Munksøgård have a number of votes based on size of their apartments. Between the general assemblies, the steering board can take decisions within their mandate. Besides this system, discussion/information meetings (common meetings) are organized throughout the year. Everyone can participate at these meetings, influence the discussions and make proposals for the steering group or general assembly.

The existing heating system

Munksøgård's heating system consists of a heating central which is connected to the five building groups through local district heating pipes. The heat flow in Munksøgård's heating

system is obtained from measurements and is presented in Figure 2. There are three boilers in the heating central; two wood pellet boilers and one oil boiler serving as back-up. Their respective sizes are 200kW, 60kW and 250kW. Hot water storage tank connected with a solar heating plant is installed locally in each housing group. It covers around half of the hot water consumption. The total heated area is 9300 m² with an average net heat demand of 50 $\frac{\text{kWh}}{\text{m}^2 \text{ year}}$; 63 $\frac{\text{kWh}}{\text{m}^2 \text{ year}}$ if including heating of domestic hot water. In an average year the boilers are using around 1000 MWh of wood pellets and 110 MWh of oil.

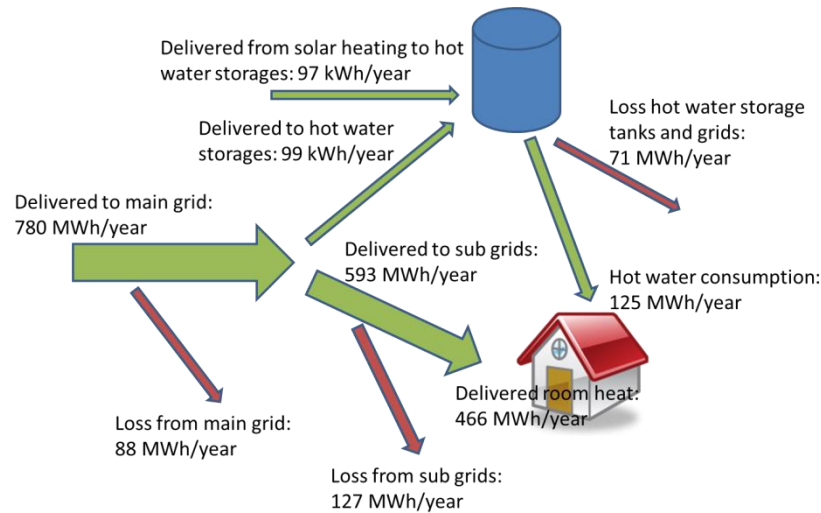


Figure 2. Heat flow in Munksøgård's heating system. The red arrows represent heat losses.

The different solutions

After a rough screening of possibilities by a local working group, three options were pointed out to be further investigated. The existing system will be used as reference to compare with the new solutions. The new solutions include: improved wood pellet boilers, local decentralized heat pumps and connection to district heating.

Improved wood pellet boilers. New generation of wood pellet boilers and monitoring and control systems can make the system much more efficient and easier to run. This solution will also include flue gas cleaning to reduce local air pollution and it will reuse all existing piping in ground. Pros and cons of this solution are listed in Table 1.

Table 1. Pros and cons of improved wood pellet boilers

Pros	Cons
Less expansive compared to other solution	Professionals are needed for repairs and maintenance
Low emission of CO ₂ (originates from transport)	Risk of breakdowns (mainly due to wood pellet transport system)
Stable operation	Big trucks with wood pellets arrive once a week in the cold period
Improved local air quality	Depends on limited biomass resources
Locally known technology	Flue gas system creates noise

The improved wood pellet boilers will not affect the landscape or cause inconvenience to the inhabitants during installation.

Local decentralized heat pumps. This solution entails installation of five ground-source heat pumps - one in each housing group. This means that the central heating grid will not be used and can be shut off. To supply the heat pumps with adequate amount of heat, pipes with brine have to be buried in a sufficient area. A rule of thumb is that $40 \frac{\text{kWh}}{\text{m}^2 \text{ year}}$ of horizontal area can annually be retrieved in Denmark. This solution will result in five independent heating systems. Pros and cons of this solution are listed in Table 2.

Table 2. Pros and cons of local decentralized heat pumps

Pros	Cons
No noise	Needs thorough monitoring and regulation
Low CO ₂ emission (from electricity production)	Will not be able to deliver enough heat in the coldest periods (needs electric supplement)
Less maintenance	Leakage in underground pipes is difficult to find and repair
No local air pollution	A big ground area is needed for the underground pipes
Fits well into the future Danish energy system	

GIS analysis confirmed that there is enough ground area to be able to extract enough heat from the ground and thus cover heating demand.

District heating. Munksøgård is placed near Roskilde district heating grid. Only a short connection pipe is needed to connect Munksøgård's local heating network with the central district heating grid. The district heating network in Roskilde is linked to the grid in the Copenhagen area and thereby supplied by several CHP (Combined Heat and Power) plants and waste incineration plants (and some back-up boilers). Pros and cons of this solution are listed in Table 3.

Table 3. Pros and cons of connection to Roskilde district heating grid

Pros	Cons
No noise	Heat price is set by Roskilde Forsyning (the local distribution company)
No local air pollution	Breakdown on main district heating grid will influence heat supply at Munksøgård
Very little maintenance	
Minimum need for monitoring and regulation	
Fits well into the future Danish energy system	

The planned decision process

Taking a decision on the future heating system at Munksøgård is a democratic process where many factors influence the choice of the residents. The final decision will depend on a voting at the general assembly meeting where each household can vote. The factors influencing the choice can be economical, environmental, practical and emotional. Lack of knowledge will leave it up

to people's beliefs about these factors. Therefore, to remove as much uncertainty as possible a process lasting more than a year has been started:

1. An “expert” group was established in spring 2014 to describe the different technical solutions, their costs and impacts. Posters have been produced describing each solution. This group was supported by a professional energy consultant.
2. On a meeting in June 2015 where all residents are invited the solutions and posters will be presented and people will have the possibility to ask questions to the “expert group”.
3. The posters will be put up in each of the five common houses during the summer of 2015 to encourage people to discuss pros and cons of the different solutions.
4. After summer of 2015 a full day workshop will be organized. The workshop will end up with a clear indication of the preferred solution.
5. Shortly after this workshop the matter will be treated on the general assembly meeting and a voting between the solutions will be carried out.
6. A detailed feasibility study will be started for the chosen solution.
7. The new heating system will be implemented.

LOCAL SPREADSHEET MODEL

To compare the different solutions for the community a spreadsheet model focussed on the private economy was developed. It analyses the yearly energy balance for Munksøgård's heating system and the costs and impacts from the possible solutions. A snapshot of the model is shown in Figure 3. In the model, all three alternative solutions are compared against the existing system. It is possible to make different assumptions about fuel costs, heat savings, solar heating share, etc. Technology data sheets provide the model with efficiencies, costs and emission factors.

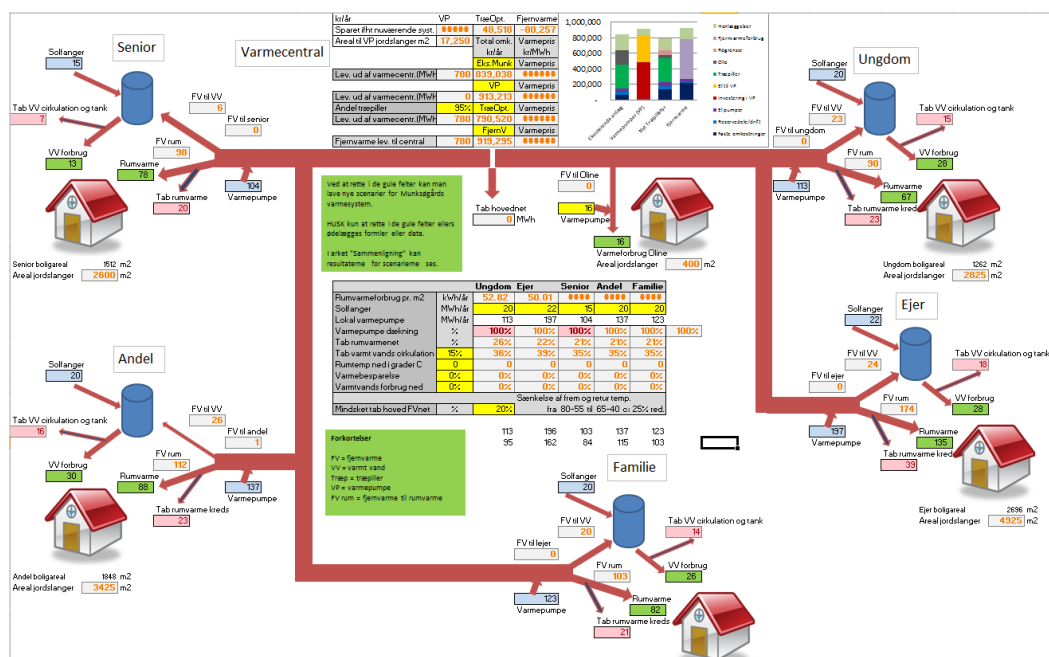


Figure 3. Munksøgård Heating System Model.

Results from the private-economic analysis

Two sets of results from the spreadsheet model are presented. First, the total private-economic annual costs for each of the solutions are presented in Figure 4. This is the price which

consumers need to pay for space heating and domestic hot water. Second, air pollution is presented in Figure 5 and the socio-economic costs related to these emissions are presented in Figure 6 for each of the solutions.

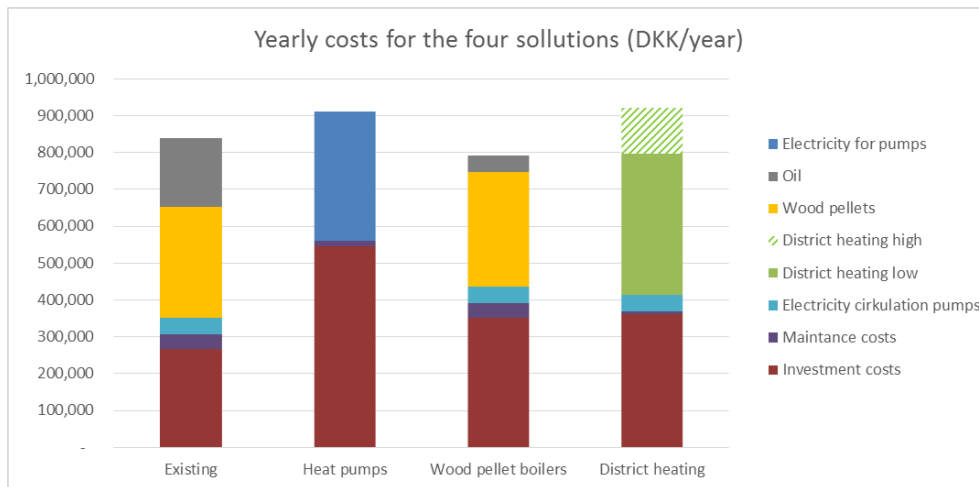


Figure 4. Annual costs for the four systems divided on costs types.

There are two main types of annual costs: the costs of paying for the investment and the fuel costs. The heat pump solution has large investment costs mainly due to digging down many kilometres of pipes to retrieve heat from the ground. The fuel consumed by the heat pumps is electricity bought from the grid. The solution with wood pellet boiler and the district heating solution are very close in costs when using the optimistic assumption for district heating. The uncertainty with the district heating solution is whether the district heating company overtakes the local main grid at Munksøgård. If so, they will deliver the heat directly to each house. If not, the district heating company will deliver the heat to the local main grid, while Munksøgård will be operating this grid. The latter is more expensive to Munksøgård as the heat loss from the Munksøgård's main grid is then included in their heat consumption.

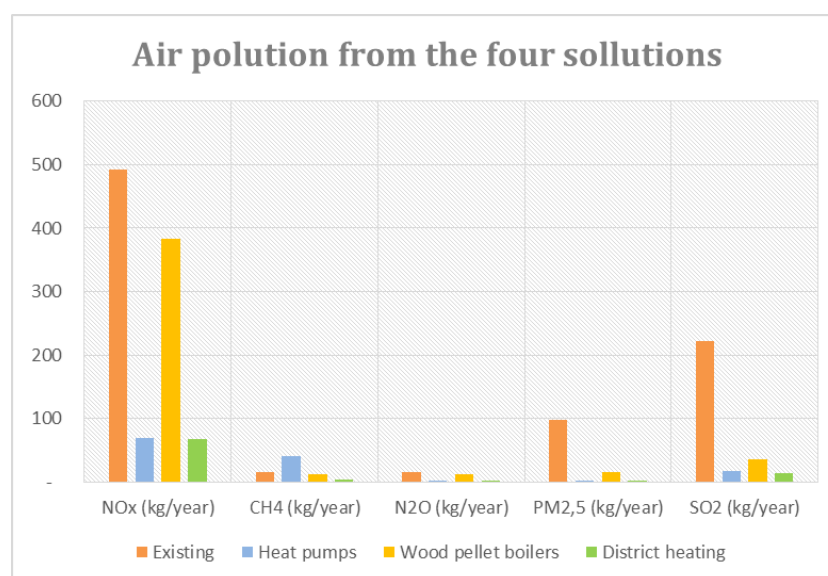


Figure 5. Air pollution from the local boilers or in the case of heat pumps and district heating, from the power and heating plants delivering electricity and district heat

The air pollution can be translated into socio-economic costs from the health impacts caused by the pollutants. The price per emitted pollutant is based on the Danish research centre CEEH (Centre for Energy, Environment and Health, www.ceeh.dk).

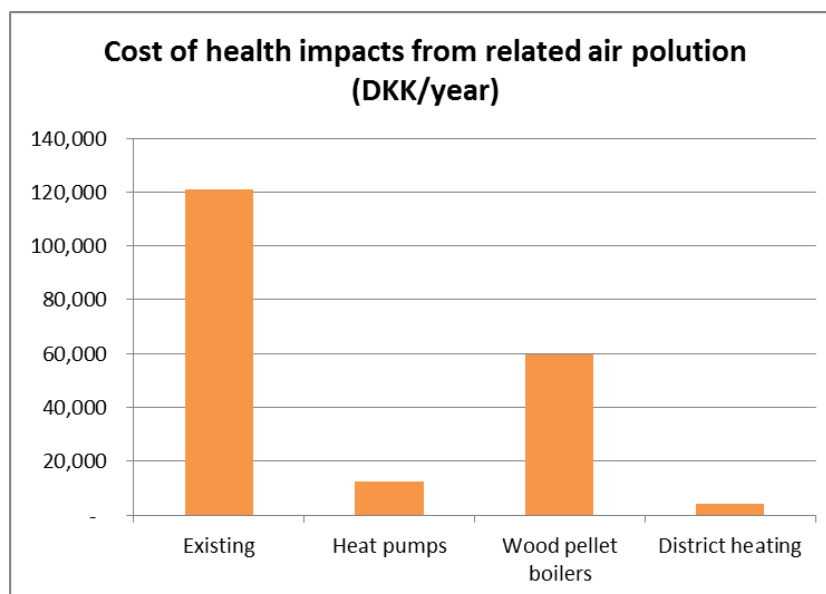


Figure 6. Socio-economic health costs from air pollution in each of the four cases.

From the private-economic point of view the implementation of new efficient wood pellet boilers are the most profitable. Even if health impacts would be somehow included (difficult because they cannot simply be added to the private-economic costs), this solution is still the cheapest. If the optimistic assumptions are used for connection to district heating then the costs of two solutions are very close.

TIMES MODELS

TIMES was developed and is maintained by the Energy Technology Systems Analysis Programme (ETSAP), an Implementing Agreement of the International Energy Agency, established in 1976. TIMES is a multi-regional, technology-rich, bottom-up model generator used for long-term analysis and planning of regional, national and multi-national energy systems. Additionally, TIMES falls within a group of techno-economic, partial equilibrium model generators assuming full foresight and perfectly competitive markets. It is usually used for simultaneous analysis of all sectors of the energy system, but can be utilised for analysis of specific sectors.

The processes, commodities and commodity flows are the basic elements TIMES models. These elements and their interrelations are presented in Figure 7 - the processes as boxes, commodities and commodity flows as vertical lines. The processes are transforming one or more commodities into one or more different commodities. The commodities consist of: energy carriers (wind, solar radiation, coal, etc.), energy services (heated residential area, illuminated service area, etc.), materials (aluminium, copper, etc.), monetary flows (DKK, EUR, etc.) and emissions (CO₂, NO_x, etc.). The commodity flows are the links between processes and commodities. A commodity flow has the same nature as a commodity but is linked to a specific process and represents a single input or a single output of that process.

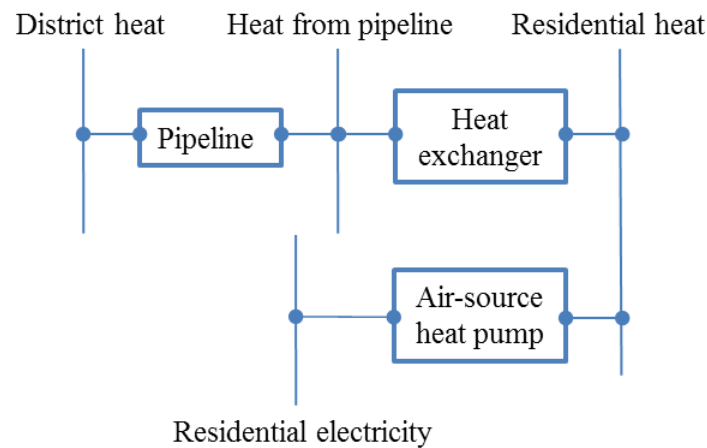


Figure 7. Basic elements of TIMES models: processes, commodities and commodity flows

TIMES-DTU MODEL

TIMES model for Denmark, named TIMES-DTU is including all sectors of the energy system. It is developed by the Energy Systems Analysis group, DTU Management Engineering, E4SMA and the IntERACT team from the Danish Energy Agency. All authors of the present paper have been members of the project team. Since the present paper deals with the choice of future heat supply, description of general features of TIMES-DTU model is followed by the description of power and heat and residential sector. The description of the remaining sectors (Transportation, Private Service, Public service, Construction activity, Manufacturing, Agriculture and Other sectors) is left out. For detailed description of TIMES-DTU model, including theoretical foundations and descriptions of remaining sectors, the reader should consult model documentation at www.ens.dk/interact.

TIMES-DTU model is national, multi-regional energy system model. Denmark is represented with two regions, East Denmark (DKE) and West Denmark (DKW). Electrical power systems of these regions are connected via 600 MW HVDC power cable, while heating systems are not connected.

Time in energy system models is often represented in a form of chronological values of same duration. The chronological structure is not established in TIMES-DTU. Instead, time is represented in form of time-slices and time-periods. Time-slices represent hours with similar characteristics within the same year. The 32 time-slices in TIMES-DTU resulted from the following aggregation:

- Four seasons in a year,
- Two periods in a week – workday and non-workday,
- Four critical situations for the Danish power system:
 - Situation A: Wind power is high while electricity demand is low. The issue of excess electricity production needs to be resolved.
 - Situation B: Wind power is low while electricity demand is high. There is a need for import or backup capacity.
 - Situation C: Peak production from PVs. The issue of excess electricity production needs to be resolved.
 - Situation D: Remaining time periods.

The time-slices have different lengths, ranging from 1 hour in case of the time-slice covering winter workdays with high wind power and low power demand, up to 1409 hours in case of the time-slice covering workdays in autumn classified as "Remaining time periods". One or more years are grouped into time-periods. The durations of time-periods are presented in Table 4.

Table 4. Durations of time-periods in TIMES-DTU

Time period	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Start year	2010	2011	2014	2018	2023	2028	2033	2038	2043	2048
End year	2010	2013	2017	2022	2027	2032	2037	2042	2047	2052
Duration (years)	1	3	4	5	5	5	5	5	5	5
Representative year	2010	2012	2015	2020	2025	2030	2035	2040	2045	2050

The domestically available and imported resources are utilised in TIMES-DTU to produce electricity, individual and district heat within the Danish energy system. The domestic potentials of non-internationally traded fuels are defined in the model. The domestic onshore wind, offshore wind and wave potentials are obtained from [30], while domestic PV, solar thermal and geothermal potentials are obtained from [31]. The domestic straw, woodchips, wood waste and slurry potentials are based on [32]. The domestic combustible waste potentials are obtained from FRIDA model [33], while waste import from abroad is not enabled for now in TIMES-DTU. The entire combustible waste potential is assumed to be incinerated in all analysed scenarios. The long-term price projections for straw, woodchips, wood waste and slurry are obtained from [34]. For internationally traded fuels, long-term price projections are obtained from [35] and their import is not constrained in the model.

Electricity trade is enabled in TIMES-DTU. The electricity interconnections with neighbouring countries are represented by physical capacities and import/export price projections from/to each of the neighbouring countries. The price projections, existing transmission capacities and planned transmission expansions are adopted from [36]. To prevent the development of the Danish energy system based on imported electricity, Denmark is constrained to be a net exporter of electricity in all analysed scenarios.

Power and heat sector

Electricity and district heat in TIMES-DTU are produced in the power and heat sector. After being produced in the power and heat sector, electricity and district heat are being transmitted and distributed to residential consumers. The state of power and heat sector in Base Year¹ is defined by installed capacities of plants producing electricity only, electricity and heat and heat only. The highly detailed level of data contained in [37] allowed for grouping of plants according to technical properties, size, fuel and geographical region. The retirement profiles are assumed based on years of commission and technical lifetimes.

Each of the existing plants is represented with efficiencies, fixed and variable O&M costs and availability factors. The plants available for installation after 2010 are additionally described by investment costs. The technology catalogue published by the Danish Energy Agency [38] is used as the source of techno-economic parameters.

¹ Base year is the starting year in the model for which the model is calibrated with the official energy statistics. In the present paper Base Year is 2010.

Residential sector

The residential sector in TIMES-DTU is an aggregate of the Danish residential building stock. These buildings are demanding electricity for lightening and electrical appliances, space heating and domestic hot water. The data about buildings in the Base Year is obtained from the BBR dataset [39]. The Danish DRY (Design Reference Year) is used as a source of weather data [40]. The net heating demand in the Base Year is calculated for 72 building groups according to the methodology presented in [41] and aggregated according to following properties:

- Construction period - buildings built before 1972, after 1972,
- Building type – Single-family and Multi-family² buildings according to classification used in Danish energy statistics [42],
- Region - DKE and DKW,
- Position relative to existing DH³ areas – Central, Decentral and Individual areas.

After the base year, heat demand in the residential sector is driven by the change in the heated area of buildings and the implementation of heat saving measures. The construction rates are calculated for each building group as a difference between housing demand and existing stock affected by demolition. The projections of housing demands are adopted from the Danish Rational Economic Agents Model (DREAM) [43], showing that housing demand in Denmark grows by 0.3 % per year. The annual demolition rate of 0.25 % of the area in 2010 is adopted from [44]. It is assumed that the heating demand of new buildings complies with building regulations [45].

There are two options for heat supply of residential buildings in TIMES-DTU: district heating and individual heating. District heating is produced at CHP and HO (Heat Only) plants and transmitted to consumers, while individual heating is produced and consumed "on site".

The division of district heating producers in TIMES-DTU on Central and Decentral is adopted from Energy Producers Count [37]. Central and Decentral DH producers are supplying buildings located in Central and Decentral DH areas, respectively. Higher heating demands, installed capacities and transmission and distribution efficiencies are the characteristics of Central compared to Decentral DH areas.

Based on the type of heat supply and position relative to existing DH areas heat supply areas are divided into three groups:

1. DH areas - the majority of buildings within DH areas is supplied by DH, but individual heating solutions may be found. Based on the previous discussion DH areas are subdivided into Central and Decentral.
2. Next-to-DH areas - these areas are sharing the border with DH areas. If they are sharing the border with Central DH areas, they are classified as Central. Otherwise, they are classified as Decentral. These areas are supplied from individual heating sources.
3. Individual areas – these areas are not sharing a border with existing DH areas. They are entirely supplied from individual heating sources.

Central, Decentral and Individual areas in DKE are presented in Figure 8. Connection of individually heated buildings within DH areas to DH as well expansion DH networks to Next-to-

² SF and MF will be denoting Single-family and Multi-family buildings throughout the paper, respectively.

³ DH will be denoting district heating throughout the paper.

DH areas is enabled in TIMES-DTU. Expansion of DH into Individual areas is not enabled. The GIS methodology used for calculating potentials and costs of district heating expansion is presented in detail in [46] and will be briefly summarized.

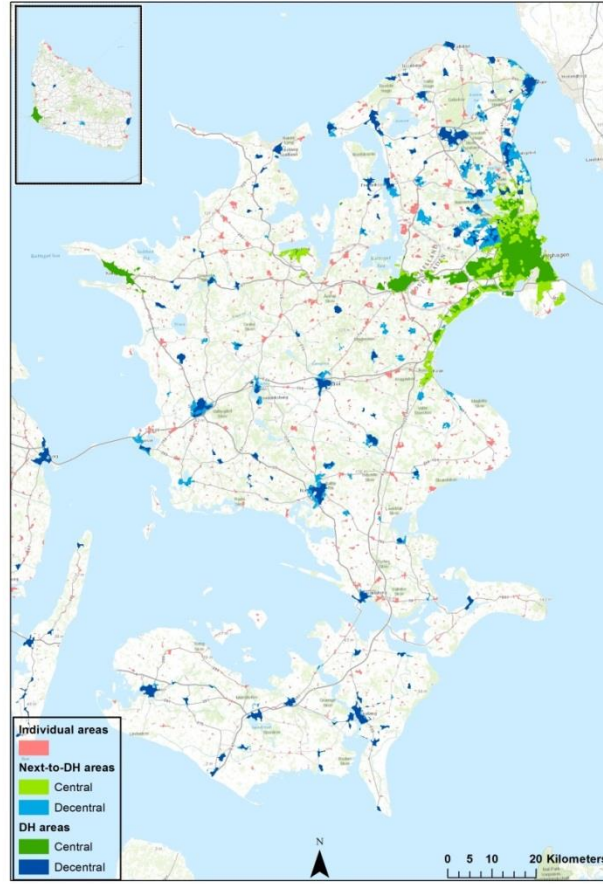


Figure 8. Central, Decentral and Individual areas in DKE

The investment costs of connecting buildings to existing DH systems are calculated for DH and Next-to-DH areas using equations (1) and (2), respectively:

$$C_{DH} = C_{CONN} = (c_{CONN,s} + c_{HE,s}) \cdot n_s + (c_{CONN,m} + c_{HE,m}) \cdot n_m + (c_{CONN,l} + c_{HE,l}) \cdot n_l \quad (1)$$

$$C_{NEXT-TO-DH} = C_{CONN} + C_{DIST} = (c_{CONN,s} + c_{HE,s}) \cdot n_s + (c_{CONN,m} + c_{HE,m}) \cdot n_m + (c_{CONN,l} + c_{HE,l}) \cdot n_l + c_{DIST} \cdot A \quad (2)$$

where used symbols have the following meaning:

C_{DH} , $C_{NEXT-TO-DH}$ - Total investment costs of connecting buildings within DH and Next-to-DH areas to existing DH systems, respectively.

C_{CONN} , C_{DIST} - Total investment costs in connection and distribution infrastructure, respectively.

n_s , n_m , n_l – Number of Small, Medium and Large buildings, respectively. Buildings with annual demand for space heating and domestic hot water lower than 50 MWh are regarded as Small, between 50 and 350 MWh as Medium and buildings with demand greater than 350 MWh are considered as Large.

$c_{\text{CONN},s}$, $c_{\text{CONN},m}$, $c_{\text{CONN},l}$ – Specific investment costs of connecting pipes for Small, Medium and Large buildings, respectively. They are expressed in $10^3 \frac{\text{DKK}}{\text{building}}$.

$c_{\text{HE},s}$, $c_{\text{HE},m}$, $c_{\text{HE},l}$ – Specific investment costs of heat exchangers for Small, Medium and Large buildings, respectively. They are expressed in $10^3 \frac{\text{DKK}}{\text{building}}$.

A - area of a specific Next-to-DH expressed in km^2 .

It is assumed that the buildings within DH areas need to pay for the connecting pipes and heat exchangers; the buildings in Next-to-DH areas additionally need to cover the cost of distribution infrastructure. In the calculation of connection costs, an assumption is made that all buildings within Next-to-DH areas are connecting to DH. The costs are annuitized with 4 % discount rate, converted into cost curves and presented in Figure 9 for Central DH and Next-to-DH areas located in DKE. Before being imported into TIMES-DTU, cumulative cost curves for expansion of district heating within DH and to Next-to-DH areas are approximated with one pair and two pairs of representative potentials and costs, as shown in Figure 10.

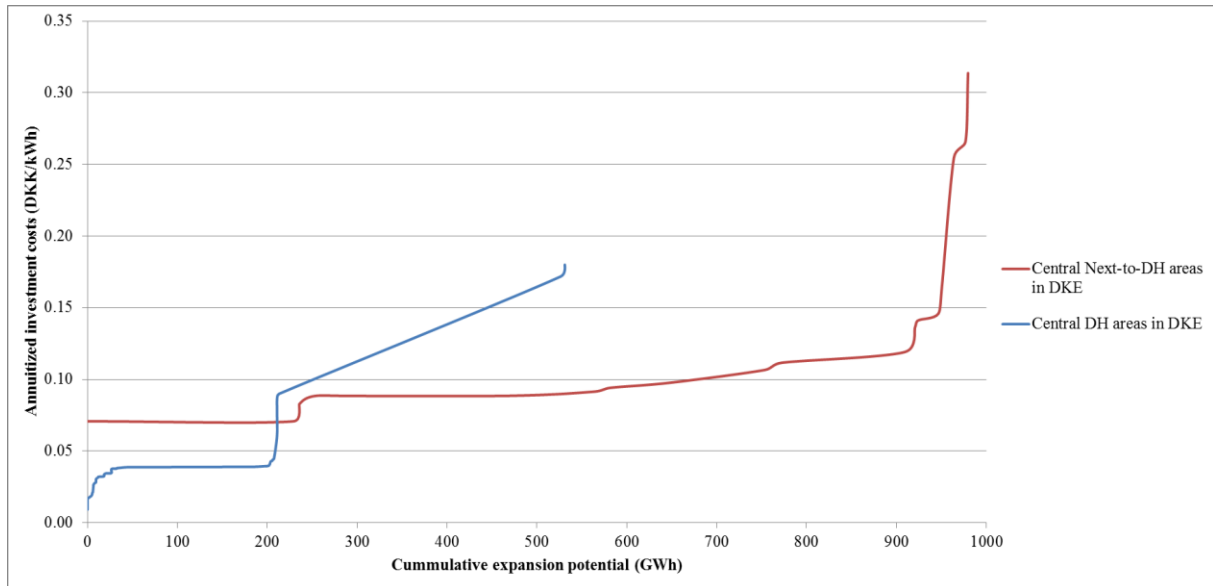


Figure 9. Cumulative potential for expansion of district heating and associated annuitized investment costs

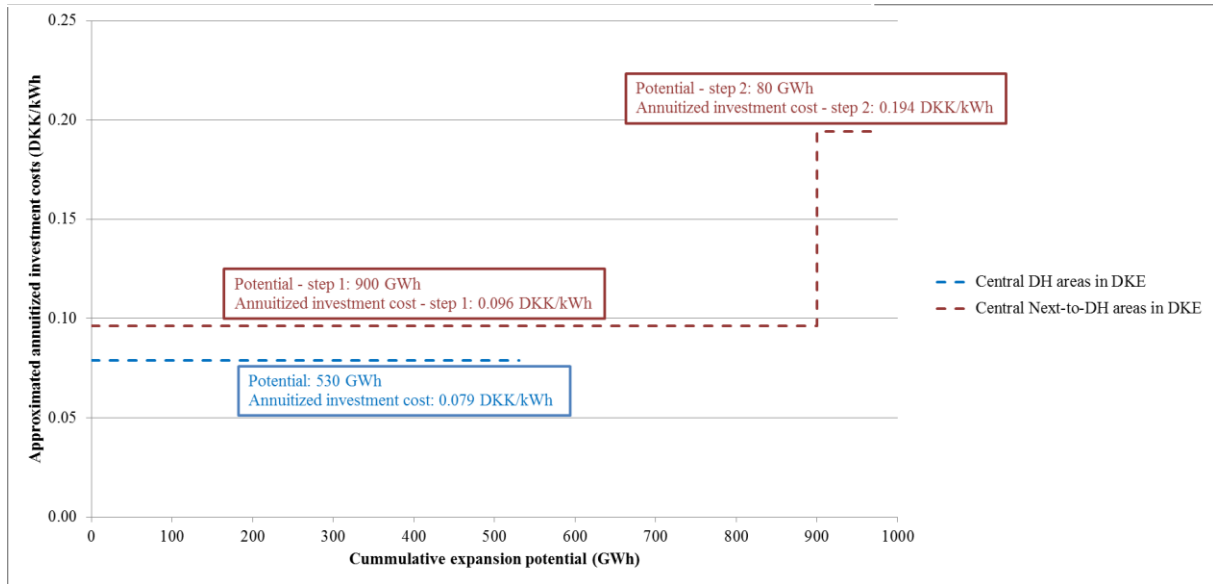


Figure 10. Approximated cumulative cost curves for district expansion

The individual heating capacities in the Base year are calculated by combining the technology catalogue published by the Danish Energy Agency [38], BBR dataset [39] and Danish Energy Statistics [42]. The decommissioning rate of 6 % is assumed for individual heating capacities. To be able to meet the heating demand after the base year, TIMES-DTU can invest in new individual heating capacities; the technology catalogue [38] is used as the source of techno-economic data.

Residential heating demand can be reduced by heat saving measures. The potentials and costs of heat saving measures are calculated for 72 building types according to methodology presented in [38]. This methodology is summarized in the following steps:

1. Residential building stock is aggregated into 9 groups according to similar construction period and 8 groups according to use, which results in 72 building groups. This division is adopted from [47].
2. For each building group several renovation levels are assumed for each element of building envelope. For each renovation level heat saving potentials are calculated as the difference between heating demand before and after renovation:

$$HS_{g,e,l} = HL_{g,e,old} - HL_{g,e,l}, \quad (3)$$

where the used symbols have the following meaning:

HS – Heat saving potential expressed in kWh per year.

HL – Heat loss.

g – One of 72 building groups.

e – Elements of building envelope, such as walls, floors, roofs, windows and mechanical ventilation systems with heat recovery.

l – Specific level of heat saving measures. Three different additional insulation thicknesses are assumed for roofs, floors and walls, four different types of windows and one mechanical ventilation system with heat recovery.

old – This subscript means "Before the renovation".

3. Total investment costs are calculated for each renovation level of each element in each building type. Total investment costs are expressed in DKK. The costs are based on [47-49].
4. Specific investment costs are calculated for each renovation level of each element in each building group by dividing investment costs calculated in step 3 with heat saving potential calculated in step 2. Specific investment costs are expressed in $\frac{\text{DKK}}{\text{kWh per year}}$.
5. For each element and each building group the least expensive heat saving level is chosen as the one with lowest value calculated in step 4. The specific investment costs are annuitized with 4 % discount rate. The least expensive annuitized specific investment costs are expressed in $\frac{\text{DKK per year}}{\text{kWh per year}}$.
6. The investment costs and the associated heat saving potentials for each element and each building group calculated in step 5 are used to construct cumulative cost curves. After that, these curves are aggregated to 24 groups according to construction period (Before 1972 and After 1972), building type (Single-family and Multi-family), position relative to existing DH areas (Central, Decentral and Individual) and region (DKE and DKW).
7. The curves from step 6 are approximated with three pairs of potentials and costs and used in TIMES-DTU. As an example, cumulative potentials and annuitized costs of heat saving measures for SF buildings built before 1972 located in Central DH areas of DKE are presented in
8. Figure 11.

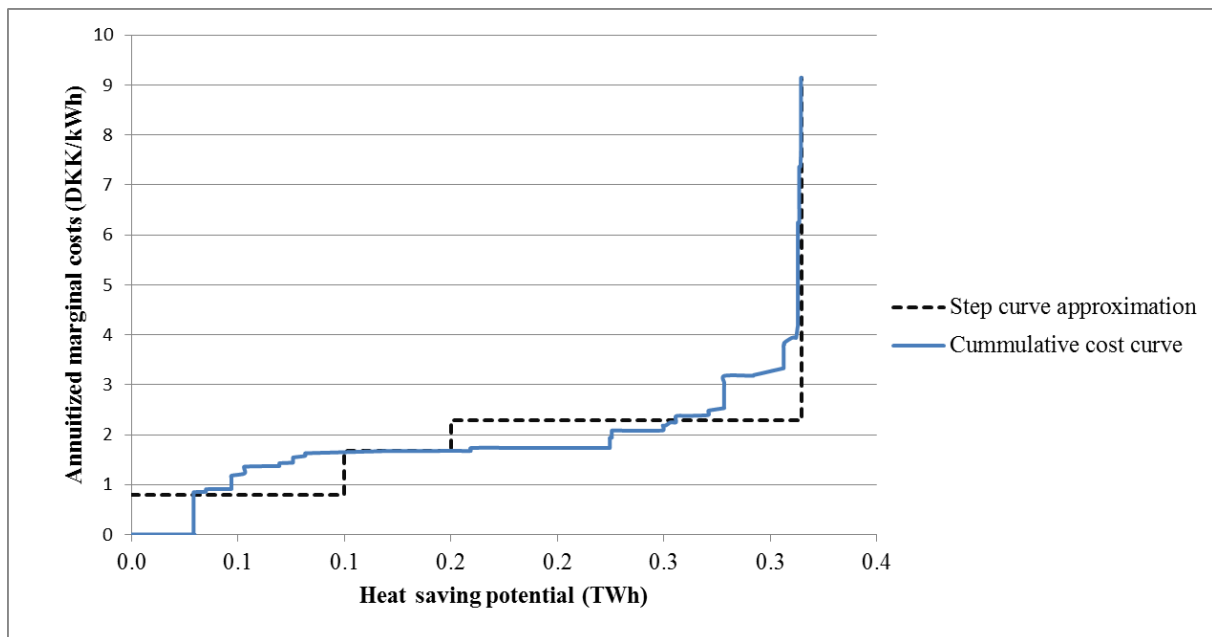


Figure 11. Heat saving potentials and associated annuitized investment costs and three-step approximation

Analysed scenarios in TIMES-DTU

Three scenarios of the future Danish energy system are compared in the present analysis utilising TIMES-DTU model:

- Base – There are no policy constraints imposed on the model. The model is searching for the optimal investments and operation while respecting only technical constraints.

- WLP (acronym from Wind Low Production) - In addition to Base scenario, at least 50 % of electricity needs to be produced from wind power starting from 2020. This renewable energy target originates from [1].
- WLP-NFE (acronym from Wind Low Production – Non-Fossil Energy) - In addition to WLP scenario, production of electricity and heat need to be 100 % renewable starting from 2035, while whole energy system needs to be 100 % renewable energy starting from 2050. This renewable energy target originates from [2].

The analysed scenarios will show how politically agreed renewable energy targets affect the optimal development of the Danish energy system. Base scenario presents the development of the Danish energy system until 2050 driven only by minimization of the total system costs. In the WLP scenario minimization of the total system costs is constrained only by the constraint that at least 50 % of electricity needs to come from wind power starting from 2020. WLP-NFE scenario shows how the gradual change from fossil fuels to renewables affects all sectors of the Danish energy system. To ensure that the model will not base future Danish electricity supply on imported electricity, annual import of electricity is constrained to be equal to or less than annual export in both all scenarios.

RESULTS FROM TIMES-DTU

According to the classification adopted in TIMES-DTU, existing buildings in Munksøgård community belong to the group of SF buildings located within Central areas in DKE. The future heat supply of this building group from the energy system point of view is presented in Figure 12. The production of district heating in Central DH plants located in DKE is presented in Figure 13. The district heat is not only delivered to residential sector, but to all sectors in DKE, including residential, industrial, public and private service, manufacturing and agricultural sector.

All results for heat supply in this chapter refer to SF buildings in Central heating areas of DKE. In Base scenario the heat supply configuration does not change until 2020. Share of district heating remains around 30 %, while only moderate heat savings are observed. In 2025, heat savings are affecting heat demand in buildings built before 1972 heated by district heating. From 2025 to 2045 significant heat saving measures are being implemented in individually heated buildings, resulting in rise of DH share to 65 %. In 2050 remaining buildings are switching to Central DH. Even though the shares vary over the analysed period, approximately two thirds of Central DH is produced at coal-based CHPs, while the remaining part is produced at waste CHPs (until 2030) and HO plants (starting from 2020).

Similar development of heat supply occurs in WLP scenario. Until 2030, DH share varies between 30 and 40 % while no significant heat savings occur. From 2035 to 2045, DH share grows from 36 to 68 % as a result of heat saving measures in individually heated SF buildings built before 1972. After 2045, all SF buildings located in Central areas located in DKE are connected to DH. Before 2030, 60 % of Centralized district heat is produced in coal-based CHPs, while the remaining part is produced in waste HO and CHP plants. From 2030 to 2050 these shares remain steady at 50 %.

Development of heat supply in WLP-NFE scenario can be divided into three periods. First, until 2020 shares of district heating and individual heating remain the same as in the Base year while heat savings play a minor role. Second, from 2025 to 2030, heat production from individual heating sources remains the same, while heat savings are reducing heat demand in buildings built before 1972 supplied by DH. Third period lasts from 2035 to 2050. In this period, significant

heat saving measures are reducing heat demand to around 50 % of heat demand from 2010, while major switch from individual heating to district heating occurs in 2035. The switch is a result of the policy constraint that electricity and heat need to be 100 % renewable from 2035 and connection to district heating appears to be more cost-effective than installation of individual boilers. After 2035, DH share remains at over 95 %. Before 2020 DH is produced from coal CHPs and waste-fuelled HO plants. Large amounts of wind power in the system and demand for renewable power and heat are setting a good basis for implementation of large-scale heat pumps. From 2020 to 2040, 50-60 % of district heat is produced from large-scale heat pumps. The remaining share consists of district heat from waste-fuelled HO plants and waste heat from fuel production. After 2040, increase in biofuel production for transport entails the increase in available waste heat and thus waste heat replaces the production large-scale heat pumps.

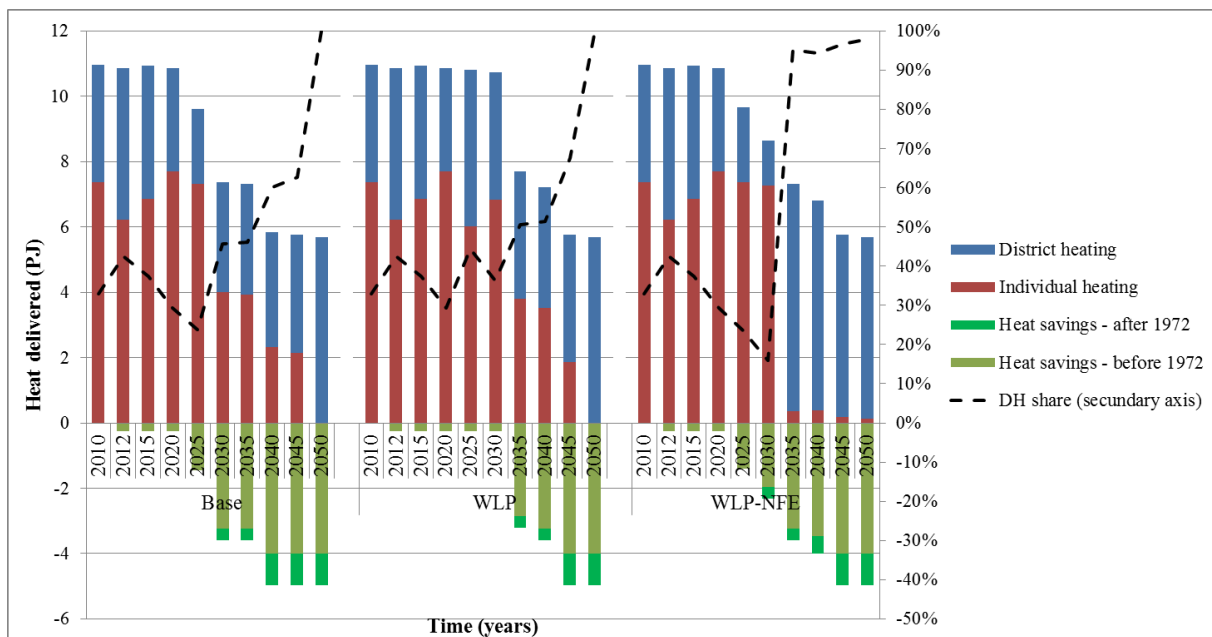


Figure 12. Heat supply to SF buildings located within Central areas in DKE

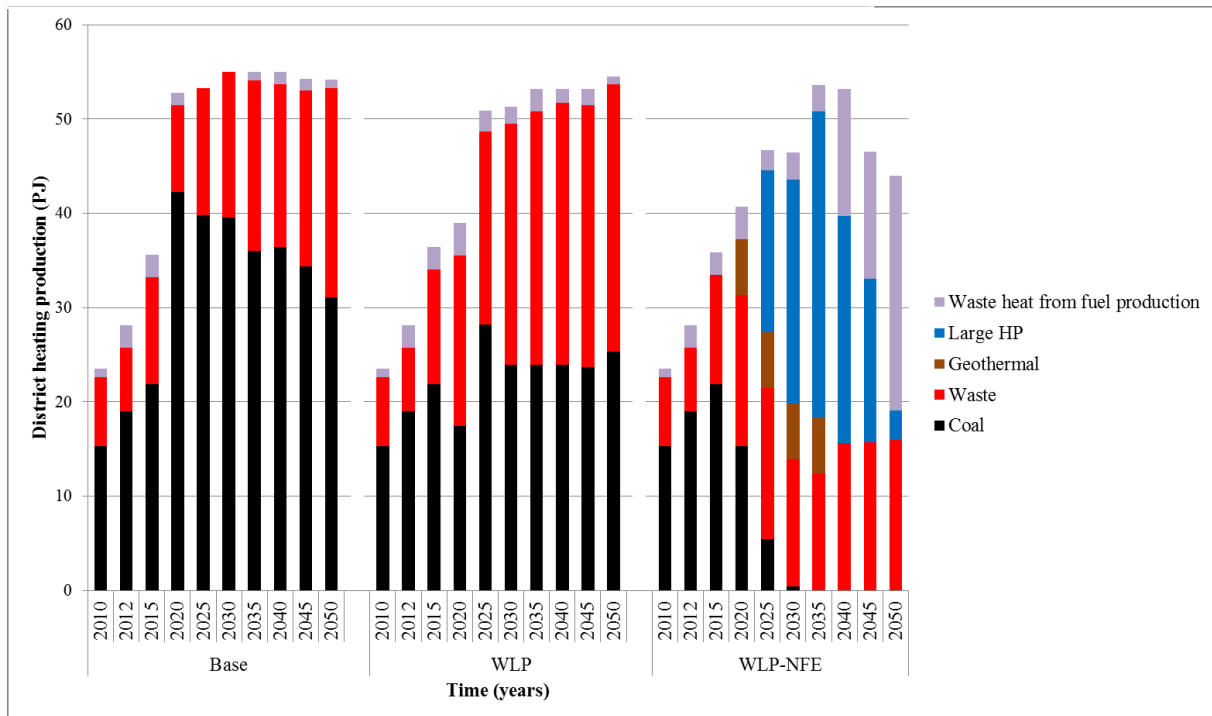


Figure 13. Production of district heating from Centralized plants located in DKE

The development of heat supply from individual heating options is presented in Figure 14. The development until 2035 is uniform in Base and WLP scenario, while in WLP-NFE scenario "100 % renewable power and heat" constraint dictates the switch to renewables. The capacities existing in Base year are "dying out" and reinvestments in these technologies are not made. In all scenarios investments in natural gas heat pumps are made starting from 2015, while in WLP-NFE investments in air-source heat pumps are made in 2035.

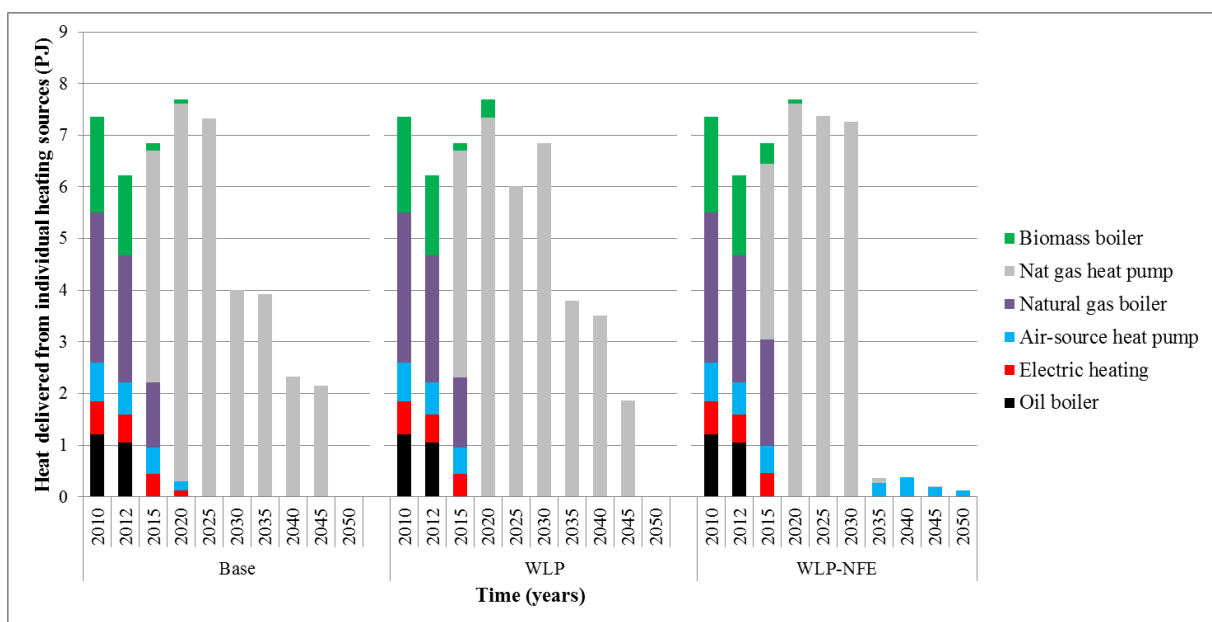


Figure 14. Heat delivered from individual heating sources to SF buildings located within Central areas in DKE

Results from TIMES-DTU represent optimal solution for Danish energy system as whole, i.e. the development of Munksøgård is not explicitly modelled. However, general conclusions regarding future heat supply in Munksøgård can be drawn based on the national-level analysis. The buildings in Munksøgård belong to the group of SF buildings located within Central areas in DKE. They are supplied from biomass and oil boilers in Base Year. In all scenarios, individual oil boilers stop delivering heat to SF buildings after 2012, while share of individual biomass boilers drop after 2012 before being phased out after 2020.

Due to the target of phasing out fossil fuels for heating by 2035, natural gas is no longer an option and the solution is mainly a switch to district heating and in smaller part to air-source heat pumps. The advice for a long-term solution from the TIMES-DTU model is therefore to switch to district heating. In medium-term the results indicate that it could be interesting to introduce natural gas heat pumps. However, the gas grid is further away from Munksøgård than the DH grid and the connection costs to the gas grid have not been included in the investment costs.

The conclusion, considering local conditions, is therefore that Munksøgård should connect to the DH grid in Roskilde. It can also be concluded that reduction of heat consumption by 5-10 % should be achieved by implementing heat saving measures - this could be reached by replacing all windows with more efficient ones.

CONCLUSION

Due to increasing amount of breakdowns, residents of Munksøgård housing community decided to change the local heating system. Issues of this kind are usually analysed by energy consultants from a private-economic point. Instead of that, the present paper analysed three different points of view – private-economic, private-economic with included externalities and socio-economic. The decisions will be made in a democratic voting process.

Private-economic considerations were analysed with a spreadsheet model of the local heating system. Different solutions including connection to nearby district heating network, local decentralized heat pumps and new wood pellet boiler have been compared with existing system. New wood pellet boiler is the least expensive solution, even though connection to nearby district heating network has very similar costs. The main uncertainty in this analysis is whether the district heating company will measure the heat delivery at each individual consumer or to the housing community as one. The latter is more expensive to Munksøgård. Due to high installation costs, local decentralized heat pumps were uncompetitive with other solutions.

Socio-economic considerations were analysed with TIMES-DTU model of the whole Danish energy system. An analysis until 2050 was performed. The buildings in Munksøgård were not explicitly modelled, but represented by a group of single-family buildings, built after 1972 and located in Central areas of East Denmark. The connection of these buildings to district heating proved to be optimal for the energy system as a whole. This is especially pronounced in the scenario in which production of electricity and heat is 100 % renewable from 2035.

From the private economic analysis, an improved wood pellet based boiler system turned out to be the best choice. Even when taking monetised health cost from air pollution into account it still comes out the best. The evaluation of noise, workload and other inconveniences cannot be priced easily. They will though influence the choice of the residents, as these things are very relevant in the daily life at Munksøgård.

What remains now is to follow the democratic process at Munksøgård and see which solution the residents choose. If possible, this result will be included in the final paper.

Comparing socio-economic and private economic evaluations of specific projects are important learnings for decision makers. If socio-economically sound policy targets are put up, then it needs to be ensured that these solutions perform the best private-economically as well. Otherwise, it cannot be expected that individuals will follow the optimal road for the society. This can be solved by introducing relevant policy measures such as supporting schemes, taxes and regulation.

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